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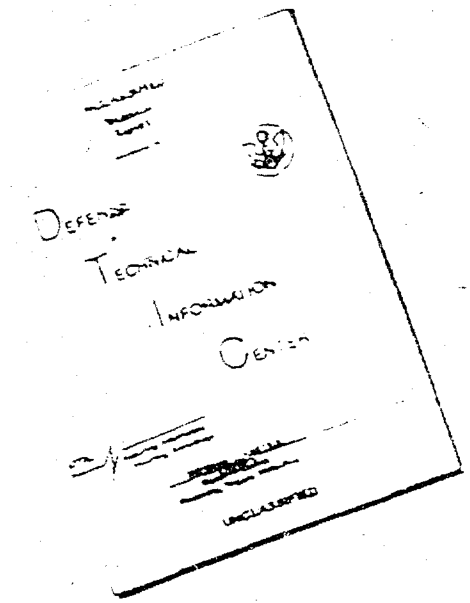

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FRACTURE EXTENSION RESISTANCE (R-CURVE) CHARACTERISTICS FOR THREE HIGH-STRENGTH STEELS

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The effect of specimen thickness on the R-curve slope was investigated for three high-strength steels of high, intermediate, and low resistance to ductile fracture. R curves were determined for each steel in the full thickness (1 in.) and for thicknesses of 0.625 and 0.325 in. The R-curve slopes showed good agreement for each section size, and a transition in the fracture mode from flat fracture at short crack extensions to the metal's characteristic degree of shear fracture for long extensions was observed for each steel. The data can be described by an exponential equation involving fracture energy, specimen cross-section dimensions, and a constant R_p which is proportional to the R-curve slope. For each steel, R_p is unaffected by changes in the specimen geometry, thus indicating it to be a material property.

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ABSTRACT

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PROBLEM STATUS

This report completes one phase of a continuing problem.

AUTHORIZATION

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FRACTURE EXTENSION RESISTANCE (R-CURVE) CHARACTERISTICS FOR THREE HIGH-STRENGTH STEELS

INTRODUCTION

Recently, procedures based on the Dynamic Tear (DT) test have been evolved for characterizing the fracture extension resistance of structural metals (1-3). The level of fracture extension resistance is expressed in terms of the resistance (R) curve slope, which defines the energy for fracture as a function of incremental crack extension. Increases in the R-curve slope are related to increases in the resistance to fracture extension for ductile metals; flat (no slope) R curves are obtained for the case of brittle metals. Further, it was shown that for steels, titanium alloys, and aluminum alloys the R-curve slope characteristics can be defined by an expression relating the fracture extension resistance, in terms of energy per unit crack extension, to the specimen geometry, and a constant related to the inherent fracture resistance of the material.

This report describes the results of a study for three ductile high-strength steels in which it is shown that specific R-curve slope features are basic to a given material regardless of section size aspects. This study also indicates that, for a given material, accurate predictions of the level of fracture resistance can be made by specimens of different geometries.

R-CURVE FACTORS

The characteristic behavior of a metal under conditions of forced crack extension is directly modeled by the R curve (1,4). Rising R curves for ductile metals reflect the sequence of events at the crack tip in the initial phases of crack extension. Starting from a sharp crack with a straight front, the initiation of fracture is the same for all cases, i.e., a high degree of constraint is present at the onset of crack extension. The breakdown of crack-tip constraint and the formation of crack-tip plastic zones are demonstrated by the transition from the flat fracture mode to some degree of oblique shear fracture. Flat fracture is a result of the plane strain constraint, while shear fracture results from the breakdown of constraint. Fracture mode transitions are illustrated in Fig. 1 for full-shear (top) and part-shear part-flat (bottom) fracture modes. The constraint to through-thickness deformation due to a triaxial stress state is a maximum at the center of the initial crack front; the initial plane strain crack extension takes place at the center, so that the shape of the advancing crack is either "V" or "U". The length of the "V" section or the plane strain "tongue" approximates the crack extension length for the initial R-curve rise. Metals with a high-slope R curve effect a rapid transition to full-shear plane stress fracture. After the transition to full shear is complete, the crack front becomes straight. Metals with a lower degree of ductility do not evidence a complete shear fracture mode but instead show a part-shear part-flat (mixed mode) fracture resulting in a lower slope R curve.

During the R-curve rise, the crack-tip plastic zone also grows to its characteristic size, which is related to the intrinsic fracture resistance of the metal. This is evident in Fig. 2, which shows plastic zone development with fracture extension for both brittle (top) and ductile (bottom) metals. For the brittle case, the plastic zone is quite small and remains

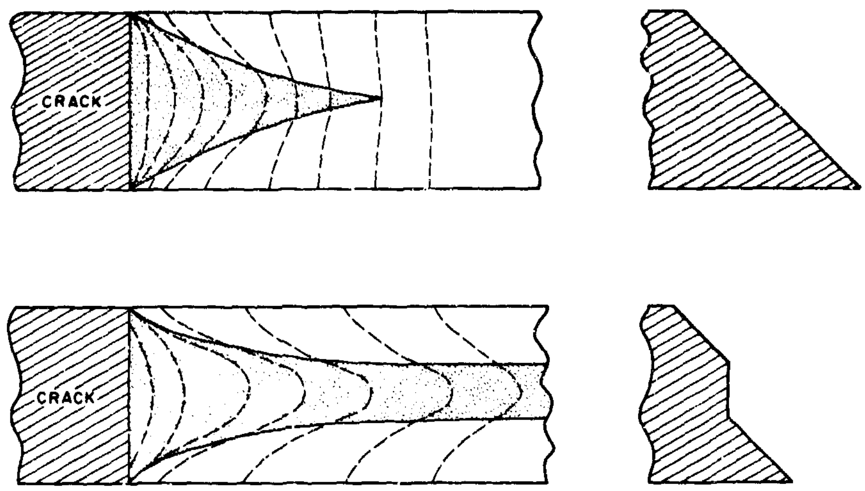


Fig. 1 — An illustration of the transition in fracture mode from initial plane strain constraint to full-shear plane stress fracture (top) and part-flat part-shear mixed mode fracture (bottom). The initial R-curve rise for ductile metals evolves from the transition from initial plane strain constraint to the degree of plane stress fracture propagation which is characteristic of the material.

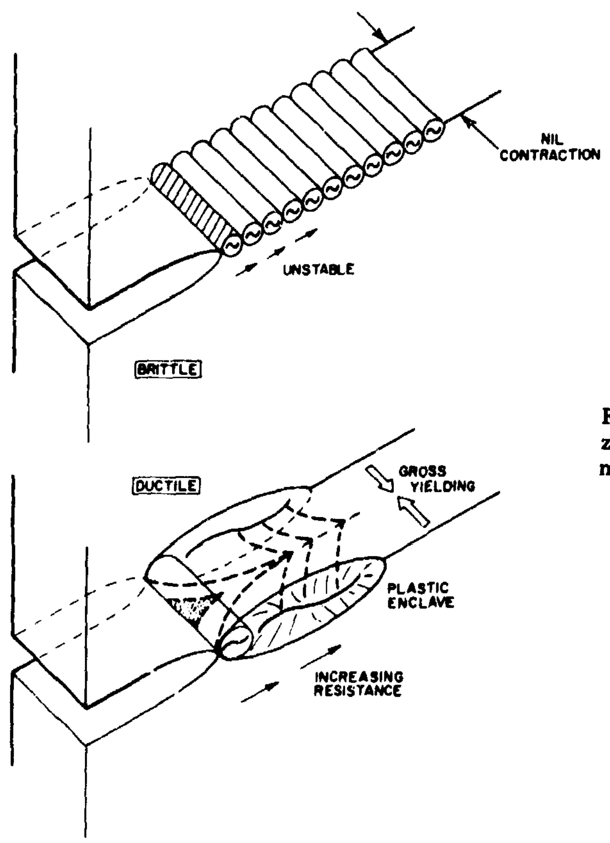


Fig. 2 — Schematic illustration of crack-tip plastic zone formation with crack extension for brittle metals (top and ductile metals (bottom).

constant in size for continued unstable crack propagation. In ductile metals, through-thickness flow and yielding at the crack tip occur as a result of the constraint breakdown. In metals with a high degree of fracture resistance, the crack-tip plastic zone becomes very large and the yielding becomes a general rather than a local process. The breakdown of constraint and the through-thickness yielding result in the loss of the initial crack-tip acuity. All of these factors combine to require increases in energy to sustain the crack extension process.

The R curves for ductile metals are not expected to rise indefinitely. At some value of crack length, the transition is complete and a constant plastic zone size that is typical for the metal is attained so that the energy per unit extension required to continue crack propagation should become constant.

The important part of the R curve is the initial rise. For metals in a wide range of fracture properties, the resistance to ductile fracture does not appear to differ significantly at small values of crack extension; however, large differences in fracture resistance become quickly apparent as the moving crack becomes longer. This is illustrated in Fig. 3 by schematic R-curve forms for metals of high-R and low-R characteristics and for a brittle metal. Full-constraint tests based on fracture initiation criteria (typically K_{Ic} tests), as depicted at point 1 in the figure, have very little ability to discriminate between the three metals. While plane strain configuration tests of the energy measurement type, such as the Charpy V, show a limited ability for discriminating between the metals, the plane stress type tests, which measure energy for a significantly long crack extension, accurately define the wide differences in fracture resistance that exist in these metals.

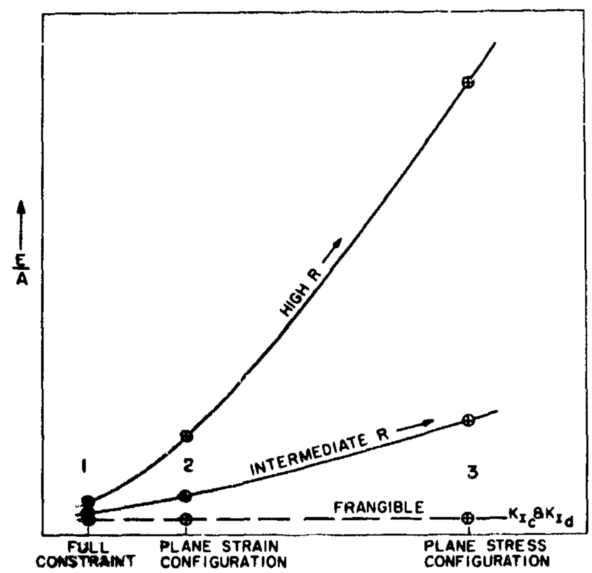
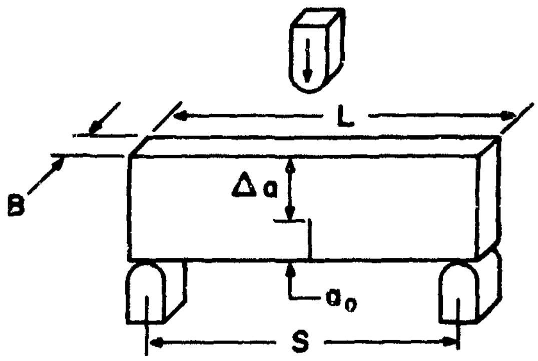


Fig. 3 — Schematic illustration of R curves for metals of high and intermediate levels of resistance to ductile fracture and a frangible metal. The effect of crack-tip constraint on the energy required for fracture extension is illustrated. The ability of different test methods to accurately present the true metals properties is related to the crack extension provided in each test specimen.

DYNAMIC TEAR TEST PROCEDURES FOR DETERMINING R CURVES

The Dynamic Tear (DT) test was designed (5,6) to determine the fracture resistance of high-strength metals in different thicknesses over the full range of strength and toughness. Because the DT test provides a direct model of the crack extension process under conditions of maximum severity with respect to crack-tip acuity and dynamic loading, and has the capacity for direct energy measurement, it was readily adaptable to R-curve determinations. The specimen is shown schematically in Fig. 4, along with dimensions of specimens used for this investigation. Adjusting the Δa dimension for a given specimen thickness permits determination of the R curve by otherwise standard procedures. R curves are plotted from simple energy-per-area calculations; this procedure does not permit separation of initiation and propagation energy, but instead combines these into one value. Standard DT test specimens are of the plane stress configuration type which permits development of the natural fracture mode. The DT R-curve test methods effectively model the fracture mode transition and place emphasis at the important initial R-curve rise.



B		S		a_0	
IN.	CM	IN.	CM	IN.	CM
1	2.5	16	40	1	2.5
.63	1.6	6	15.3	.5	1.3
.33	0.8	6	15.3	.5	1.3

Δa VARIABLE

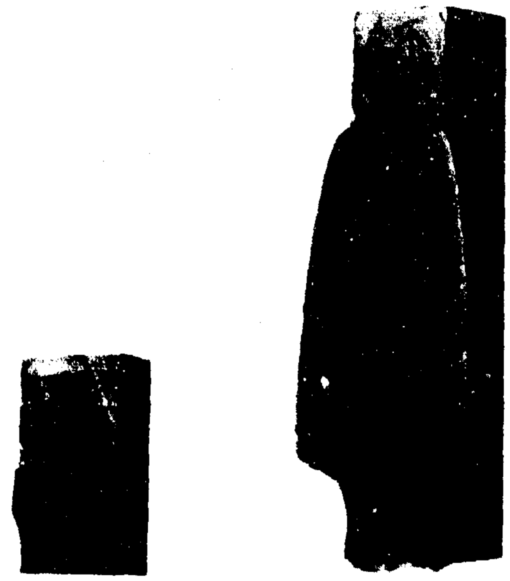


Fig. 4 — Dynamic Tear test specimen adapted for R-curve studies. The dimensions refer to configurations used in this investigation. The two fractures illustrated show the appearance of plane strain and plane stress fracture.

MATERIALS AND PROCEDURES

Three 1-in.-thick steels of nominal HY-80 composition with a wide range of strength and toughness properties were selected to study the effects of specimen thickness on the R-curve characterization. The test materials were letter coded according to their level of fracture resistance: H (high R), M (medium R), and L (low R). The chemical compositions of the three steels and their mechanical properties are given in Tables 1 and 2, respectively.

A series of DT-type R-curve specimens with nominal thicknesses B of 1 in., 5/8 in., and 3/8 in. were machined from each of the three test materials. Each series consisted of specimens of $\Delta a/B$ ratio of approximately 1, 2, 3, and 4, making a total of twelve specimens for each steel. The beam span was 16 in. for the 1-in.-thick tests and 6 in. for both the 5/8- and 3/8-in.-thick tests. The 1-in.-thick specimens had titanium-embrittled electron-beam-weld flaws (a_0 in Fig. 4) that were 1-in. deep, and the 5/8- and 3/8-in.-thick specimens had 1/2-in.-deep machined notch flaws that were sharpened by a pressed knife edge to a depth of 0.007-0.009 in.

The DT R-curve specimens were fractured in pendulum-type machines where possible, and in drop-weight-type machines when necessary due to the nonstandard geometry. All of the specimens were tested at temperatures where the fracture resistance was maximum, i.e., above the temperature transition in fracture toughness. In conducting the tests, it was found that the 4:1 specimens of 5/8 in. thickness were excessively stiff, resulting in significant deformation at points of loading. For this reason, values for these specimens are not reported.

Table 1
Chemical Composition of Steels Used for R-Curve Studies

Specimen Code	Primary Chemical Composition (%)							
	C	Mn	Si	P	S	Ni	Cr	Mo
H	0.19	0.32	0.20	0.007	0.004	3.20	1.62	0.72
M	0.20	0.43	0.21	0.006	0.007	3.28	1.66	0.75
L	0.20	0.43	0.21	0.006	0.007	3.28	1.66	0.75

Table 2
Mechanical Properties of Steels Used for R-Curve Studies

Specimen Code	YS (ksi)	UTS (ksi)	RA (%)	El (%)	Shelf DTE (ft-lb)
H	144	159	61	18	6650
M	125	141	61	19	4390
L	162	185	48	14	1450

Table 3
Fracture Test Results for
the Three Steels

Thickness B (in.)	Crack Run Δa (in.)	Fracture Energy (ft-lb)	E/A (ft-lb/in.^{2})
STEEL H			
1.02	1.0	1330	1300
1.02	2.0	3300	1620
1.03	3.0	6550	2120
1.04	4.0	11400	2740
0.65	0.64	370	890
0.64	1.29	921	1130
0.64	1.87	1925	1620
0.35	0.43	102	627
0.34	0.79	218	810
0.34	1.17	399	1005
0.30	1.52	578	1270
STEEL M			
1.01	1.0	714	706
1.02	2.0	2086	1040
1.02	3.0	4388	1440
1.03	4.0	8000	1940
0.65	0.64	186	445
0.64	1.29	673	818
0.62	1.87	1363	1170
0.31	0.43	65	502
0.32	0.79	156	622
0.34	1.16	298	755
0.34	1.53	450	867
STEEL L			
1.03	1.2	353	286
1.03	2.0	714	346
1.03	3.0	1454	430
1.04	4.0	2468	594
0.64	0.63	92	230
0.60	1.29	246	324
0.63	1.88	550	465
0.34	0.43	37	252
0.36	0.79	78	279
0.36	1.19	163	379
0.35	1.52	255	476

RESULTS

The fracture energy values and specimen cross-section dimensions are presented in Table 3. The R curves for each steel are presented in Figs. 5-7 for thickness values of 1, 5/8, and 3/8 in., respectively. In each figure, the R curves show the same form and order, i.e., in each case steel H has the highest R-curve slope, followed by steel M, with steel L having the lowest R curve. The shape of the R curves is independent of thickness. The fracture surfaces corresponding to the data points are also shown in Figs. 5-7. In each of these figures the transition in fracture mode (flat to shear) is apparent for each thickness.

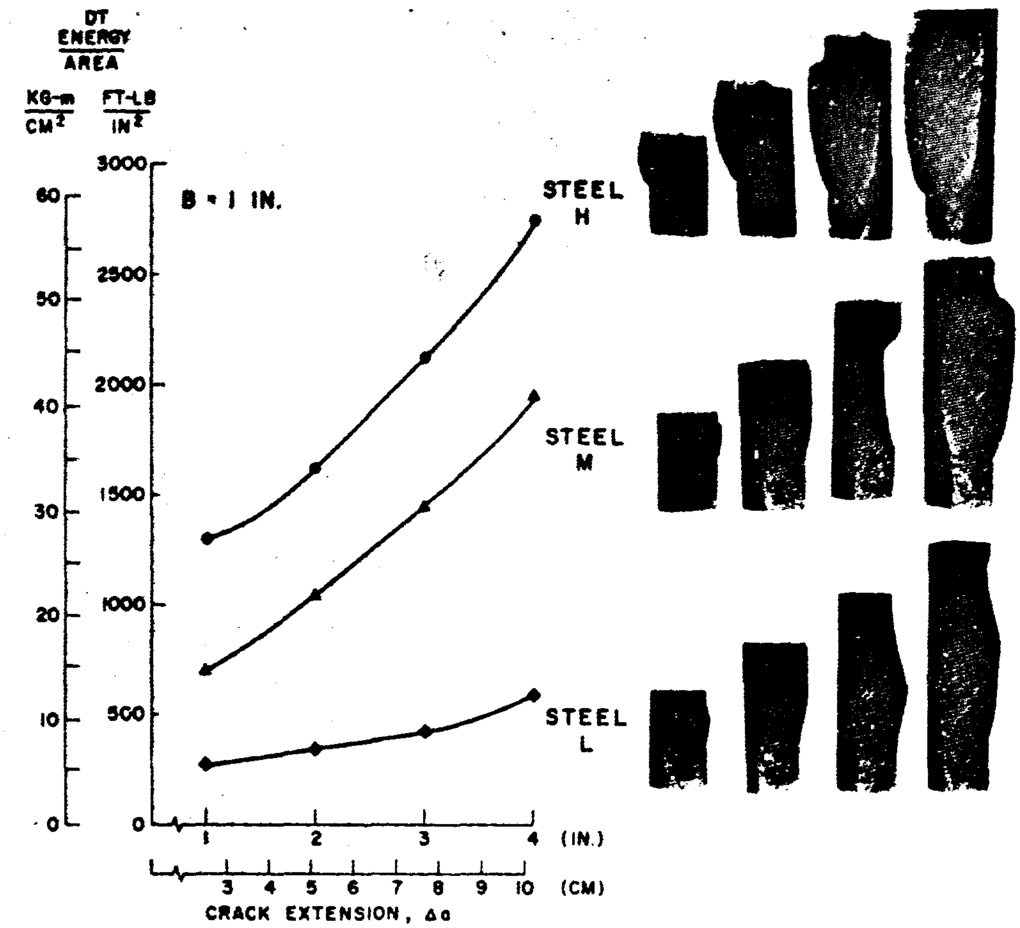


Fig. 5 — R curves for the three test steels in the full 1-in. thickness. The fractures illustrate the transition in fracture mode for each steel.

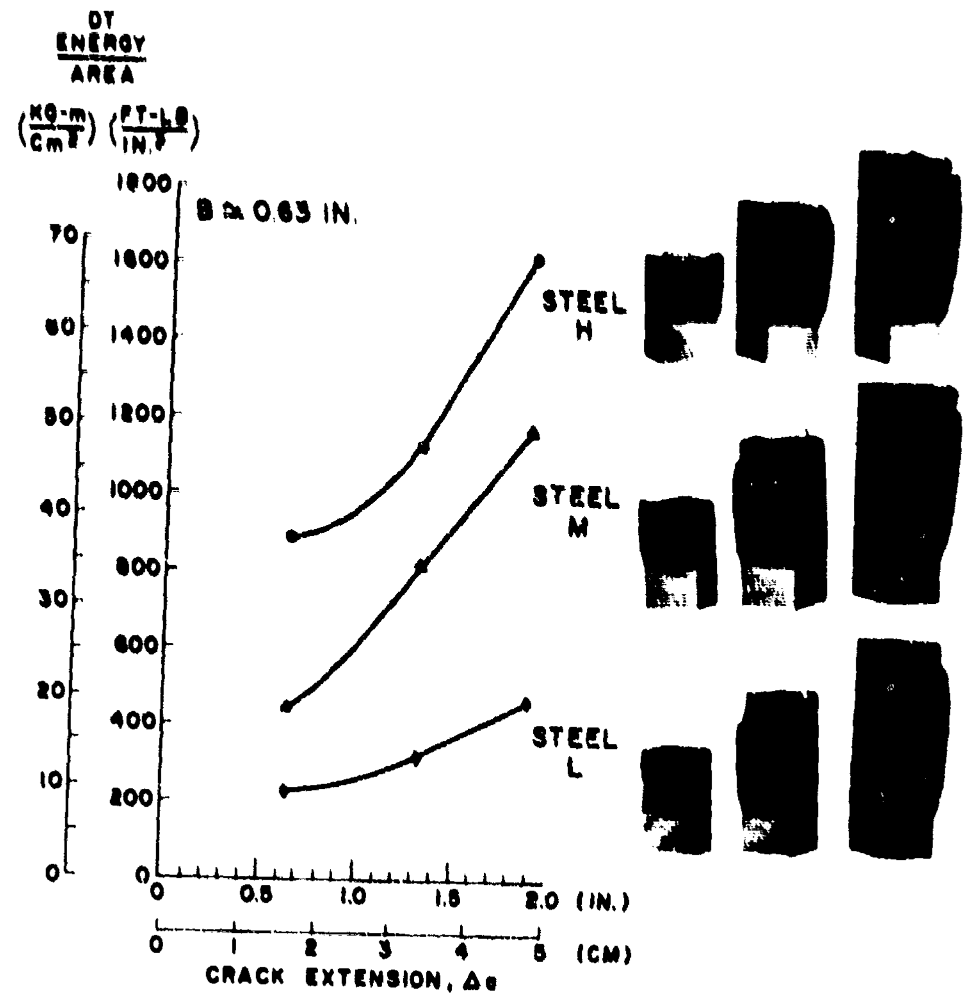


Fig. 6 -- R curves for the three test steels in 5/8 in. thickness. The fractures illustrate the transition in fracture mode for each steel.

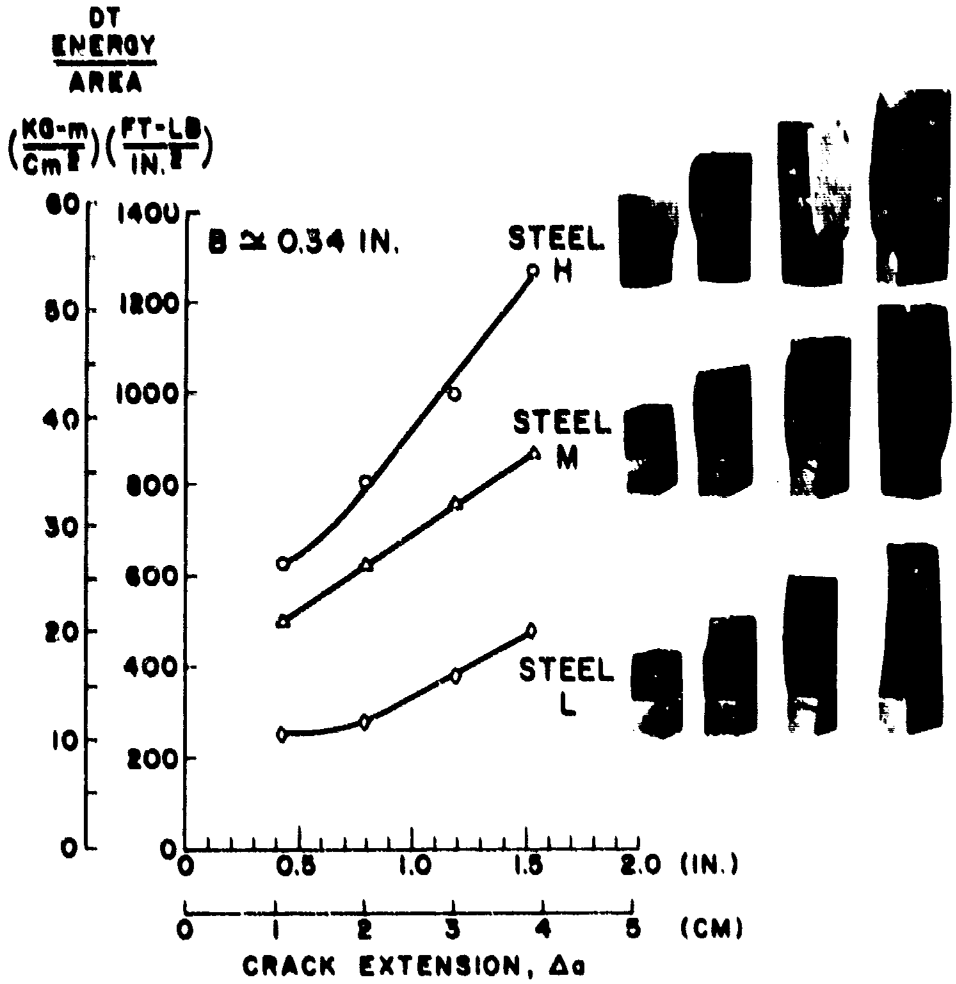


Fig. 7 — R curves for the three test steels in 3/8 in. thickness. The fractures illustrate the tran.ition in fracture mode for each steel.

All plane strain configuration specimens had a flat center with minor shear-lip formation. For steels H and M, a transition to complete shear fracture was observed for all thicknesses. Steel L did not manifest full-shear fracture in any of the thicknesses tested, even at the 4:1 geometry; however, an increase in percent shear fracture can be noted for the thinner specimens. The natural fracture extension mode for this steel is part-shear part-flat for all thicknesses above 3/8 in.

DISCUSSION

The physical significance of the R curves for steels and other metals has been well defined in the references. It is necessary to demonstrate that the R-curve form is a characteristic of the material and that the effect of decreasing the thickness of the specimen below full plate thickness decreases the energy-per-area values but does not change the form of the R curve. Figures 5-7 show that the R curves have the same form at each thickness, and the fractures illustrate the transition in fracture mode with increased fracture length for each steel at each thickness. Thus, the effect of decreasing specimen thickness is restricted to lowering the E/A values, but the R-curve shape is unaffected.

A log-log plot of the fracture energy vs the crack run for all three steels (Fig. 8), demonstrates the geometric effects of specimen dimensions and the predictability of R-curve form. In Refs. 1 and 7, it was observed that an exponential equation involving Δa, B, and a constant R_p could be used to describe the relations between these factors. The plots in Fig. 8 are a family of parallel straight lines for each steel; this indicates that a single equation can be employed to describe this system. Note that the plane strain configuration (1:1) specimens do not fit the curves.

The equation $E = R_p B^x (\Delta a)^y$, where x and y are unknown exponents and R_p is a constant associated with the inherent resistance to fracture of the material, describes the relation between DT energy and specimen geometry. The quantities R_p, x, and y can be determined for each steel. The exponent y is the slope of the families of parallel lines in Fig. 8. The quantity R_p and the exponent x are determined by substituting the values of E at the intercepts of the curves where $\Delta a = 1$ into the equation and solving the resulting three equations in two unknowns for the best solution. Reasonably consistent values of x and y determined for all three steels by this procedure are shown on Fig. 8 and in Table 4. To isolate the independent variables pertaining to geometry, the quantity $B^x (\Delta a)^y$, where x and y have average values of 0.8 and 1.9, respectively, was calculated for each data point and plotted against the quantity E/R_p in Fig. 9. The agreement shown in Fig. 9 is very good when the normal variations in plate properties from specimen to specimen and expected variations due to experimental factors are considered.

In previous work on two steels with section sizes up to 3 in. thick (7), the exponents in the equations were determined to have the values x = 0.5 and y = 2.0. For practical purposes, the exponents for the steels of this study approximate these values. This is illustrated in Fig. 10, which is a plot of E/R_p' vs $B^{0.5}(\Delta a)^2$, where R_p' = the average value of R_p shown on the figure determined with the appropriate exponents. All the data points, including the 1:1 specimens, were used for this average; notice that the 1:1 specimens are all above the exact correspondence line in Fig. 10. Eliminating the 1:1 points and recalculating R_p' results in the chart of Fig. 11, which shows the best correspondence of the three. Thus, the equation can be taken as $E = R_p B^{0.5} (\Delta a)^2$ without any apparent effect on the capability to predict DT energy values as a function of specimen geometry. This is possible for these data because

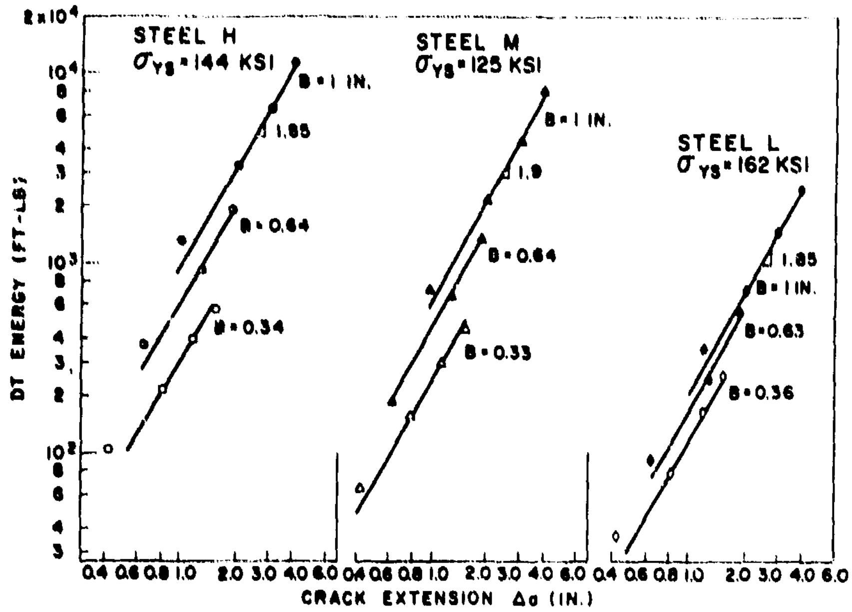


Fig. 8 — Log-log plot of the DT test data for three steels. Different Δa scales are used to prevent overlapping of the plots.

Table 4
Values x, y, and R_p in the Plastic Fracture Equation $E = R_p B^x (\Delta a)^y$

Specimen Code	Exponents		Constant
	y	x	R_p
H	1.9	1.0	980
M	1.9	0.9	625
L	1.9	0.6	213

the values of the exponent x in the range of 0.5 to 1.0 for the thicknesses involved are not as significant as the values of y. In other words, the effect of thickness on the energy for ductile fracture is of secondary importance to the effect of the length of the fracture.

The reasons why the 1:1 specimens do not fit the equations are not exactly known. One possible reason is that because of the small value of Δa in relation to the thickness, the compressive plastic zone formed under the striking tup interferes with tensile plastic zone formation during crack propagation. The significantly different stress field which exists for a large segment of the short specimen would not be a problem in specimens of larger Δa. This factor is part of the reason that short-run fracture tests, such as the C_v, are not sensitive to differences in fracture resistance. This is illustrated by the fact that C_v tests are unable to correctly define temperature transition curves for high-strength steels (8), etc.

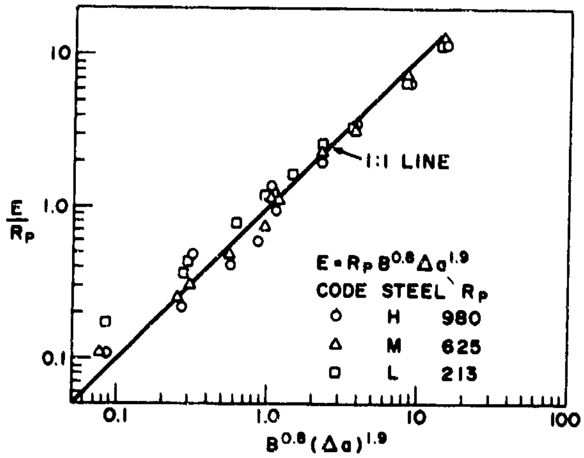


Fig. 9 — Illustration of the validity of the form of the plastic fracture equation. The exponents x and y have average values of 0.8 and 1.9, respectively.

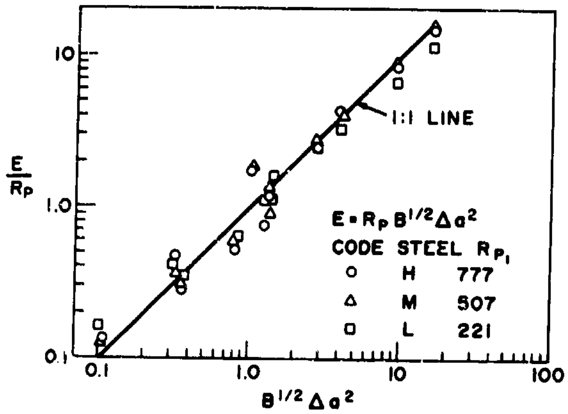


Fig. 10 — DT data fitted to the plastic fracture equation with the exponents x and y equal to 0.5 and 2.0, respectively. The plane strain (1:1) data are included in this plot.

It is necessary to show that R_p is a constant for each of the test steels because, for each steel, the degree of R-curve rise is dependent only on R_p and the thickness involved. In comparing the fracture resistance of steels at a constant thickness (Figs. 5-7), the relations between the different steels are reflected only as the relations between the different R_p values. The fact that R_p corresponds to the intrinsic fracture resistance of each metal is underscored by the consistency of the geometrical factors shown for each steel (Figs. 9-11). It is important to note that the standard 5/8-in. DT specimen (5) has the dimensions $B = 0.625$ in. and $\Delta a = 1.25$ in. (so that $\Delta a/B = 1.8$), for which $B^{0.5}(\Delta a)^2 = 0.996$ or, effectively, 1.0. Thus, the standard 5/8-in. DT specimen can be used directly to determine the R_p value.

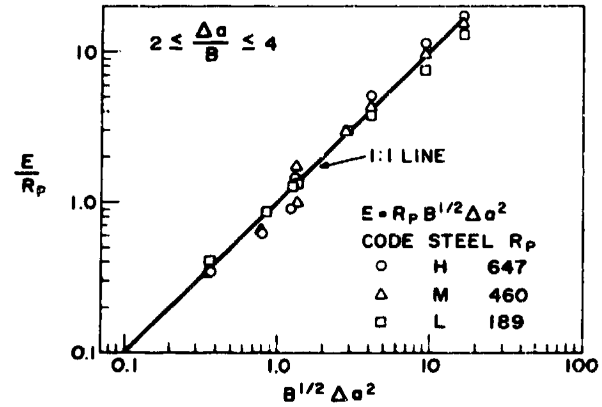


Fig. 11 — Same as Fig. 10, except that the 1:1 geometry points are omitted

Another item of interest in this study was the lack of any effect of specimen span on the energy measurements. Spans of 16 in. for the 1 in. thickness and 6 in. for the smaller specimens were utilized without an observable effect. This indicates that the fracture energy is dependent on the stress level that must be applied to cause metal separation, and thus the fracture energy — or R_p — for a given cross-sectional geometry is a property that is intrinsic to the metal. The limitations of beam span for valid DT testing are defined by stiffness factors. The upper limit of usable Δa values at a constant span is the point where excessive deformation at the loading points begins. For this study a $\Delta a/B$ value in excess of 4.0 would require an increase in the beam spans to lower the forces required to attain the critical stress for fracture.

SUMMARY

The most precise methods of defining conditions for fracture in structural design apply only to the least desirable materials. The principles of linear-elastic fracture mechanics enable calculations of critical flaw sizes at specific stress levels only for those materials which fracture at elastic levels of stress. The vast majority of structures are fabricated from metals for which brittle fracture is not expected. For these applications, other methods of analysis must be derived.

The R-curve concept for ductile metals is based on the principle that the resistance to fracture increases with crack extension to the point of energy "saturation" due to plane strain to plane stress transition effects. Fracture extension resistance is accurately modeled by the R curve from both the basic fracture mechanism aspect and the practical structural design aspect. The descriptive parameter in this rationale is the slope of the R curve; the easiest way to define this quantity is by impact tests of modified DT specimens.

One-in.-thick steels of high, medium, and low resistance to plastic fracture extension were tested in three different thicknesses to show that the R curve is constant for each material. The R curves showed good agreement for all three section sizes, and for each thickness the fractures demonstrated the constraint transition with increased crack extension. Curve fitting procedures showed that an exponential equation of the form $E = R_p B^x (\Delta a)^y$

could be used to describe the system of equations for all three steels. Average values of the exponents x and y were determined to be x = 0.8 and y = 1.9 for all three steels; this is in good agreement with the values x = 0.5 and y = 2.0 determined for other steels.

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